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The increasing use of small unmanned underwater vehicles (UUV's) for scientific, military and security applications has led to the development of new sensor technologies. Key among these has been the development of small, light, cost-effective side scan sonar systems, enabling small vehicles such as the REMUS and CETUS II to perform a variety of survey-type missions. New developments in side scan technology are increasing the capabilities of these systems, going beyond the simple detection of targets. Use of high frequencies such as 1.2 and 2.4 MHz can provide a sufficient degree of resolution for the recognition and identification of targets. The performance of these sonar systems will be discussed, as well as factors affecting performance such as speed, altitude, depression angle, and vehicle system interference.

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High Frequency Side Scan Sonar for Target Reacquisition and Identification

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***Abstract* – The increasing use of small unmanned underwater vehicles (UUV's) for scientific, military and security applications has led to the development of new sensor technologies. Key among these has been the development of small, light, cost-effective side scan sonar systems, enabling small vehicles such as the REMUS and CETUS II to perform a variety of survey-type missions. New developments in side scan technology are increasing the capabilities of these systems, going beyond the simple detection of targets. Use of high frequencies such as 1.2 and 2.4 MHz can provide a sufficient degree of resolution for the recognition and identification of targets. The performance of these sonar systems will be discussed, as well as factors affecting performance such as speed, altitude, depression angle, and vehicle system interference.**

I. INTRODUCTION

A. Objective

The objective of this effort was to evaluate selected sensors for the capability to perform the Very Shallow Water Mine Countermeasure Reacquire-Identify (R-I) mission and to ascertain whether selected sensors are compatible with small unmanned underwater vehicle (UUV) operational constraints such as speed, altitude and search methodology. The testing provided an analytical approach to testing side-scan sonar sensors and evaluated the ability of each sensor to capture images of mine-like objects (MLOs), which were deemed adequate for proper identification by trained personnel. Additionally, images were captured while varying operational parameters (vehicle altitude, sonar range, speed over ground, and angle transducers) in an effort to determine an effective R-I side-scan sonar system configuration and operational parameters for a UUV.

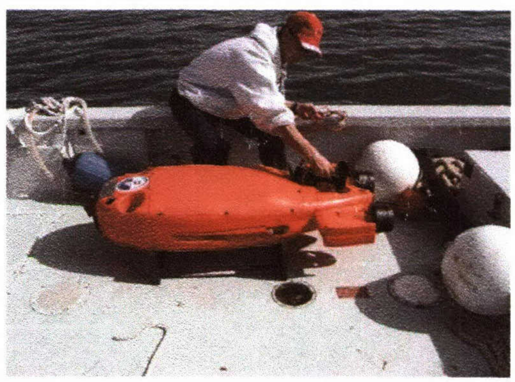
B. Approach

Based on earlier laboratory testing [1], the Marine Sonic Technology, Ltd. (MSTL) Sea Scan® PC [2] operating at a frequency of 2.4 MHz demonstrated favorable results and warranted further investigation. The testing performed in January 2003 was intended to further characterize the sonar, particularly in regards to its operation on a small UUV platform under open-water conditions. There was also the additional opportunity to test and compare a customized 1.2 MHz side-scan sonar, also manufactured by MSTL, to the 2.4 MHz unit in the same target field.

System testing was conducted in San Diego littoral waters. The goal was to evaluate the sonar systems in a variety of configurations, both as tow bodies and installed on UUV's. Five different configurations were tested:

1. MSTL towed 2.4 MHz – same unit as tested in 2002 sensor testing.
2. MSTL towed 2.4 MHz – transducer configuration similar to that used aboard REMUS and CETUS II vehicles.
3. MSTL towed 1.2 MHz – shortened aperture to improve short range performance.
4. MSTL 2.4 MHz - installed aboard Lockheed Martin/Perry Technologies CETUS II vehicle.
5. MSTL 1.2 MHz (standard length) - installed aboard EOD Mobile Unit Seven REMUS vehicle.

A.



B.

C.

Fig. 1. Test Platforms: A) MSTL tow body, B) CETUS II Vehicle and C) REMUS Vehicle

C. Background

Small UUV's, those that weigh less than 150 lbs, have many advantages for field operations over the larger models. The increase in number and capabilities of these vehicles is opening doors for an ever expanding number of applications [3]. Current and anticipated mission areas include hydrographic survey, mine countermeasure survey-classify-map, target reacquisition and identification, chemical detection and plume mapping and harbor security [4, 5]. The development of sensors such as those described here will further enhance the capabilities and utility of these vehicles.

D. Test Plan

The objective of the test was to find the configuration of the selected sonar that, when installed on a UUV, would maximize the sonar's performance in the R-I mission. The sonar parameters that were investigated included vehicle altitude, vehicle speed-over-ground, sonar swath width, vertical beam width and transducer depression angle (the angle formed by the main axis of the acoustic beam and the horizontal plane of the vehicle or tow body). On a more general level, comparison was made between the 2.4 MHz frequency and the 1.2 MHz frequency to see if the higher frequency was required in order to achieve an acceptable level of resolution for R-I.

Sets of sonar data were collected traveling down the center line of a field of MLOs along with several distracters. Distracters are objects that might appear in a sonar record as a MLO and might be found in an area where a MCM search is being performed. One of the most difficult tasks of the R-I mission is to separate the distracters from the positive targets. The type and location of all the targets were known and mapped on paper. This information was given to the sonar operator in order that the targets could be marked and annotated correctly when encountered in the sonar data.

In order to maximize the amount of data collected and have the greatest amount of flexibility in the collection of the data and the changing of the sonar parameters, a MSTL tow body was used as the primary test body. The use of the tow body allowed real-time data observation by the system operator, which allowed for the most efficient variation of sonar parameters, such as vehicle altitude, sonar range and transducer depression angle. For instance, if during testing the tow body was progressively raised above the seabed to a point that the sonar data was ineffective, that altitude could be noted and the test stopped without further collection. If a UUV was used for testing of this nature, a great deal of time would be spent in both vehicle deployment and reacquisition tasks and in transferal of the data to a suitable workstation for review. Many lines of data might have been collected at this unsuitable altitude while other parameters were being tested.

A REMUS vehicle in its current 1200 kHz configuration was used to test the ability of a small UUV to reacquire and identify a MLO in a known location using a pre-devised search method. This test was focused on the vehicle's ability to run the search pattern and reacquire the MLO, and not on the sonar parameters that maximized its effectiveness in the R-I mission.

A CETUS II vehicle with the first 2.4 MHz side-scan sonar modified for use on a UUV was present and conducted initial sea-trials and system integration work with the new sensor. Lockheed Martin and MSTL engineers were able to work together in the field learning of and dealing with vehicle integration problems as they arose. This kind of joint field work is very beneficial to both vehicle developer and sensor manufacturer.

II. PARAMETERS SPECIFIC TO THE SONAR SYSTEM

A. Frequency Comparison

Both the 2.4 MHz and the 1.2 MHz units produced R-I quality images as shown in Fig. 2. The shorter aperture on the towed 1.2 MHz unit (4" aperture, reduced from the 6" aperture normally delivered on 1.2 MHz systems) provided images of nearly the same resolution as the 2.4 MHz unit with a 3.5" aperture.

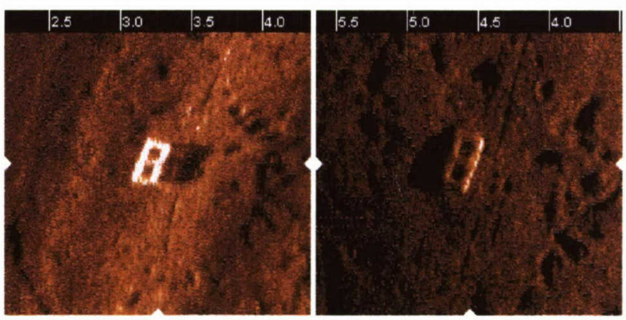


Fig. 2. Frequency Comparison. The image on the left is acquired at 1.2 MHz at a range of 3.2 m. The TVG settings were slightly too high and the echoes from the cinder block are saturated. The ability to resolve the holes in the cinder block is still clear. The image on the right is acquired at 2.4 MHz at a range of 4.6 m. With the TVG settings slightly lower, the target echoes were within the dynamic range of the system. Again, the resolution of the system is adequate to resolve the holes in the cinder block. The scale is the same for both images.

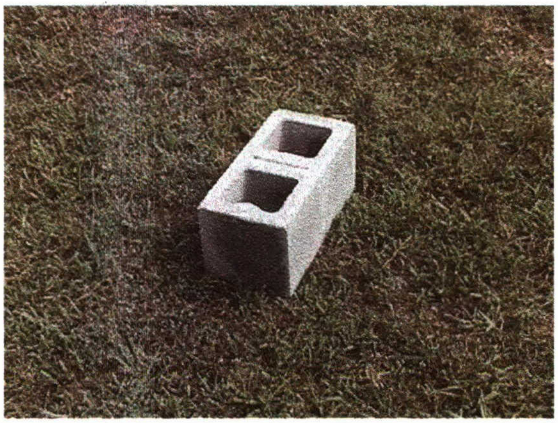


Fig. 3. Cinder Block. Standard construction cinder blocks, similar to the one pictured above, were used as distracters.

As would be expected, the higher attenuation at 2.4 MHz severely limits the effective range of the sonar. The maximum achievable range of the 1.2 MHz unit is approximately 20 meters. The maximum achievable range of the 2.4 MHz unit is approximately 10 - 12 meters.

B. Transducer Design

As part of an internal effort at MSTL to improve the beam pattern and hence the image quality of their side-scan sonar systems, two different transducer designs were brought to the testing in San Diego. There were significant differences noted between the two transducers tested, even when comparing the same frequency. The main difference occurred in the vertical beam pattern.

When using side-scan sonar, the horizontal beam width is primarily responsible for the clarity or resolution of the image. In most systems on the market today the data sampling rate and pulse repetition rate are adequate to not limit the resolution of an image. Such is the case with the Sea Scan® PC. In order to achieve the clearest possible image, manufacturers design transducers to radiate a very narrow beam in the horizontal plane. The transducers used in this experiment had horizontal one-way beam widths of 0.36° for the 2.4 MHz, 0.63° for the 1.2 MHz towed system and 0.42° for the 1.2 MHz REMUS system. As shown in Fig. 1, the image clarity is very good and very similar at the two different frequencies.

Although the vertical beam pattern does not significantly affect image clarity, it can have a significant affect on the overall performance of the sonar, appearance of the data and the operator's ability to detect MLOs. If the vertical beam width is too small, the effective range of the sonar becomes overly dependent on the altitude of the vehicle and a significant portion of the image can be disrupted by side lobes. If the beam width is too large, the image can be disrupted by surface interference and maximum achievable range is reduced due to decreased directivity index. Fig. 4 shows examples of imagery from the two different designs and is indicative of how much the beam pattern can affect the overall appearance of an image.

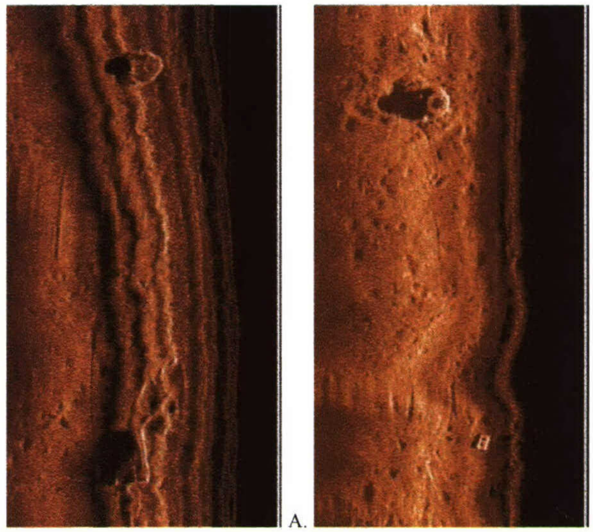


Fig. 4. Beam Pattern Effects. A) A small vertical beam width ($\leq 20°$) introduces severe side lobes which confuse the image to both human operators and CAD/CAC algorithms. A small horizontal depression angle of 5° places the side lobes directly in the imaging zone which is 50% of the imaging range. B) Increasing the vertical beam width (~30°) reduces the appearance of side lobes and consequently improves the overall appearance of the image. Increasing the horizontal depression angle (~ 20 - 25°) moves the remaining beam pattern affect out of the imaging zone and also reduces the sonar's sensitivity to surface conditions.

C. Data Acquisition Hardware & Software

During testing at such short sonar range settings (5 and 10 m) several issues with respect to the Sea Scan® PC data acquisition hardware and software became evident.

With most towed side-scan sonar systems, the towfish is flown with an altitude approximately equal to 10% of the current range setting. This is a rough rule of thumb that allows for maximum swath width while still having enough altitude for good feature shadowing which aids in identification of objects. When imaging on a 5 or 10 meter range, this rule of thumb would place the vehicle at an altitude of 0.5 to 1 m. Without adequate obstacle avoidance capabilities, this low altitude is dangerous for vehicles to maintain and 2 m or higher is preferred. This relatively high altitude wastes valuable data samples on the slant range water column between the vehicle and the seafloor. It became evident that a feature that is currently available to users of MSTL's towed products needs to be incorporated into the UUV version of the sonar control software. This feature allows the user to take advantage of the high resolution provided by the shorter range scales while "delaying" the start of the range scale a user defined amount. This feature, called Range Delay in the Sea Scan® PC software, will allow the vehicle control computer to inform the sonar system of the vehicle's current altitude. The sonar system will in turn delay the acquisition of the sonar data to optimize the ratio of bottom coverage to water column.

It was also observed that the Time-Varying-Gain (TVG) system requires finer control in the ranges of interest

during the R-I mission. The Sea Scan® PC TVG system is designed such that the user has the finest amount of control closest to the towfish. The amount of slant range signal modified by each TVG control point increases with range by a power of 2. For example, the first control point is at 0 m, the second is at 2 m, and the rest follow at the 4, 8, 16, 32, 64, 128, and 256 m ranges. When the system is used on the 5 and 10 meter range scales, only three and four TVG control points affect the image respectively. This results in rapid changes to the TVG at the control points and subsequent unnatural changes in the intensity of the bottom back scatter observed in the image.

It was also observed that it would be beneficial to increase the amount of data samples collected per channel to 1024 from the current 512. This would improve the range resolution of the system by a factor of 2. This is a software change only and is currently being implemented for testing at MSTL.

III. VEHICLE INTEGRATION ISSUES

One of the key issues in evaluation of the side-scan sonar systems is the ability for them to function effectively on the UUV platforms of interest. As these are new sonar systems, the vehicle integration issues are only now being worked out.

A. Transducer Depression Angle

The transducer depression angle (the angle between the acoustic axis of the transducer and horizontal plane with respect to the vehicle) is an important parameter to be considered when using side-scan sonar. This depression angle affects sonar performance aspects such as maximum achievable range, target echo strength, location and visibility of transducer side lobes in the imagery and artifacts in the image due to surface scattering in shallow water. The reduction in maximum achievable range is not important in the R-I mission due to the fact that the imaging range will most likely be shorter than the maximum range of the sonar. The requirement for high resolution dictates the short imaging range. Due to the short ranges and relatively high altitudes required for the R-I mission, a high depression angle of 20-30° was determined to provide the best images. It was found that this high "angle of attack" did not adversely affect the targets echo strength and still provided good shadows for aid in target identification. The wider vertical beam width (30°) is necessary in this configuration for overall image clarity.

B. Vehicle Interference

Anytime a sensor is installed into a UUV, there are significant vehicle integration issues in regards to noise interference in the sonar record that must be considered. Typically, these noise interference issues become more problematic as the frequency of interest increases. The design of the vehicle and sensor can both play a role in the susceptibility of the overall system to noise interference. Hardware systems aboard the vehicle that are common sources of noise are DC/DC converters used in power supplies, motor controllers, high current transients on motor cables and the motors themselves on the high frequency end. On the low frequency end acoustic positioning systems, acoustic communications and occasionally vehicle structural vibrations can cause noise in the sonar system. Design considerations such as the electro-magnetic shielding that a housing provides, the amount of current allowed in switching transients, the selection of electronic components that use switching technology and the type of cabling used within a vehicle and a sensor can all greatly reduce the amount of noise interference experienced by the system. Even the proximity of sensor components relative to vehicle components can play a significant role.

For example, the initial installation of the 2.4 MHz side-scan system aboard the CETUS II vehicle resulted in a total "blanking" of the image when the vehicle thrusters were turned on, as shown in Fig. 5. When the thrusters were disabled, a usable image was obtained.

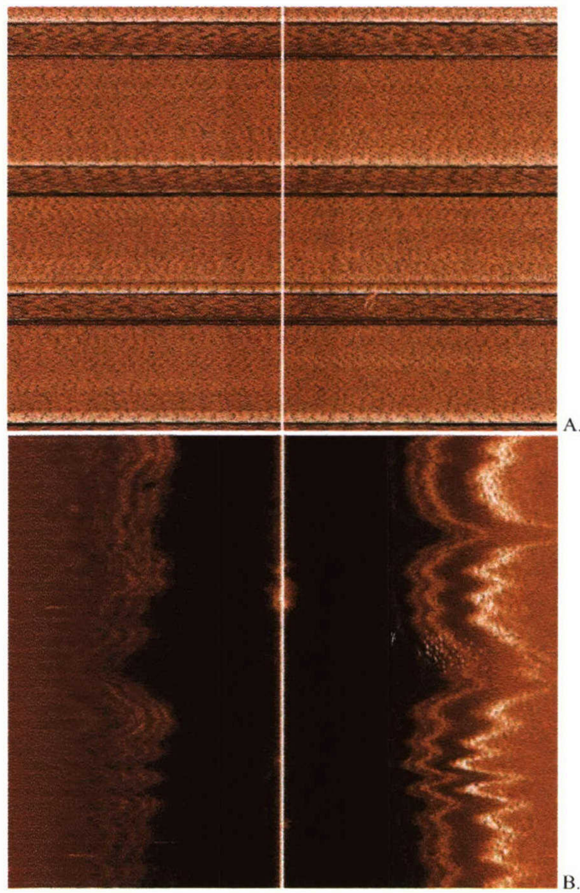


Fig. 5. Vehicle Noise. A) This image shows the interference received by the side-scan upon first installation of the sonar into the CETUS II vehicle. The noise was associated with the thrusters. B) With the thrusters disabled and the vehicle temporarily converted to a towed system, usable side-scan data was obtained as evidenced by the school of fish imaged on the right channel. Many times, dealing with noise interference in UUV's is like pealing back the layers of an onion. Once an offending noise source is found and dealt with, another becomes visible. In B, high frequency interference probably from a DC/DC converter in the vehicle is visible at the outer edge of both channels.

C. DVL Interference

Quite often, even when an interference source is known in advance and steps are taken to avoid it, surprises will arise. The RD Instruments Doppler Velocity Log (DVL) used by the REMUS vehicle operates at 1.2 MHz. It would be impossible to use filtering to remove the DVL transmissions from the side-scan record because the side-scan operates at the same frequency. In order to minimize the interference introduced into the side-scan record by the DVL, the side-scan was fitted with a "sync output" signal that triggers the DVL. This way, the DVL and side-scan transmit at the same time and the DVL burst only corrupts the water column of the side-scan record. During testing, it was noticed in the data collected by the REMUS vehicle that the side-scan imagery is often obscured by multiple transmissions from the DVL as shown in Fig. 6. It was determined that the interruptions occur when the REMUS vehicle gets close to the bottom, around 1.5 meters or less. When the vehicle altitude increased, the DVL would return to the synchronized mode, triggering off the side-scan "sync signal". The reason for this loss of sync is still being investigated.

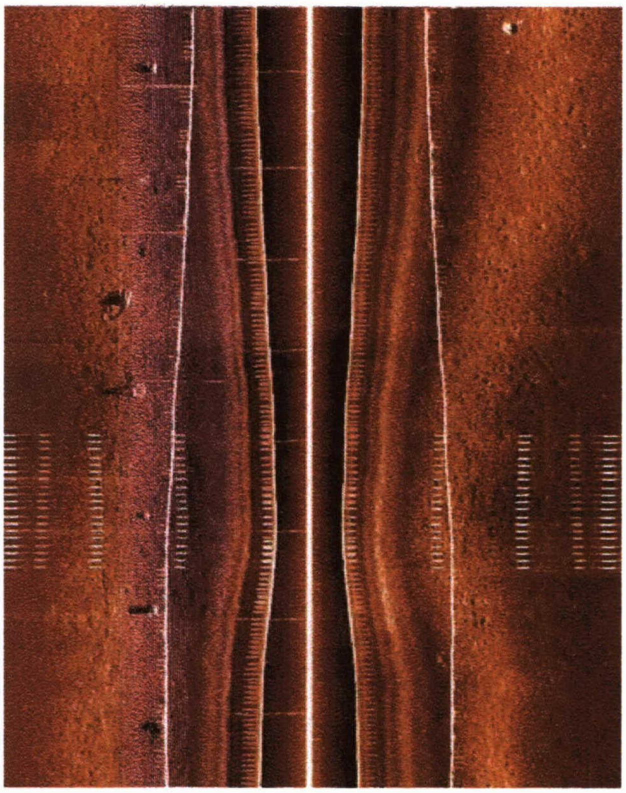


Fig. 6. DVL Interference. This image shows the intermittent interference caused by the vehicle's DVL. This data was collected by the REMUS vehicle in the same target field where most of the side-scan testing was performed. A string of MLOs can be seen in the left channel and the surface return can be seen at the same range in both channels throughout the entire image. Notice that the DVL loses synchronization with the side-scan only at low altitude. When sufficient height above the bottom is regained, the DVL and side-scan regain synchronization.

IV. OPERATIONAL CONSIDERATIONS

The way in which the vehicle is operated can greatly affect the quality of data obtained by the sonar. Many of the operational considerations are driven by the mission needs including the terrain characteristics and the coverage required, as well as the operational constraints of the platform.

A. Range and Altitude

An ideal altitude and sonar range setting must be determined such that optimal sonar imaging for identification is achieved while keeping the vehicle or tow body within its navigational abilities. When using side-scan sonar, an industry wide rule of thumb is to fly the tow body at an altitude above the bottom that is roughly 10% of the sonar range. The maximum imaging range for these high frequency sonar systems is considered to be 10 meters. In order to adhere to the industry standard of altitude = 10% of range, one would need to fly the vehicle at an altitude of 1 meter. This low altitude puts the vehicle at significant risk for bottom collisions or snags, and often interferes with the DVL operation. These tests demonstrated that an altitude of 2 meters could be maintained if the depression angle of the transducer was adjusted to 20-30°.

B. Speed

These tests demonstrated that good images could be attained at standard UUV operational speeds of 2-3 knots. Speed of the vessel or tow body is only an issue if the Sea Scan® PC software imposed speed limit is exceeded. This speed limit is dependent upon the current range setting of the sonar. As the range setting is decreased the required ping rate increases. Eventually the maximum ping rate of the sonar system is reached (either due to power consumption limits or the two-way travel time for the sound). The maximum ping rate determines the maximum speed for that range setting. At all speeds slower than the maximum, the sonar system controls the ping rate to maintain a constant square aspect ratio for each sonar image. Therefore, at all speeds below the maximum speed, the image quality is the same and vehicle efficiency and control should be used to determine optimum speed. With the current version of the Sea Scan® PC software, the maximum speed is 3.7 knots. This was demonstrated throughout the testing with good images obtained at speeds ranging from 1 to 4 knots, well within the current operational speed regime of the REMUS and CETUS II vehicles.

C. Search Path

The results of the test of the EOD REMUS with a 1.2 MHz side-scan sonar, combined with the results of the towed 2.4 MHz sonar and towed 1.2 MHz enhanced sonar, validates the use of a swimming UUV with a high resolution sonar to reacquire and identify mines that have previously been detected and classified as MLOs with a Search, Classify, and Map UUV. The test showed that the existing baseline SCM UUV vehicle can reacquire a MLO using a reacquisition block large enough to cover the stacked error

of the entire GPS/REMUS system as well as any space needed to allow the vehicle to maneuver back onto track after a tight turn. By centering the best known position of the MLO in the middle of the reacquisition block the vehicle can capture an image of the MLO. The more images that are collected from various aspects increases the likelihood that a MLO can be correctly identified as a mine or non-mine. Using the 10 meter sonar range with cross hatched 5 meter lane spacing seems to give the largest images, with the best resolution that enables identification, as well as a number of opportunities (8+) to capture the image of the mine shape. By using a + shaped reacquisition grid, see Fig. 7, the vehicle is able to line back up on the search grid after a tight turn, while minimizing the amount of area that is needlessly searched.

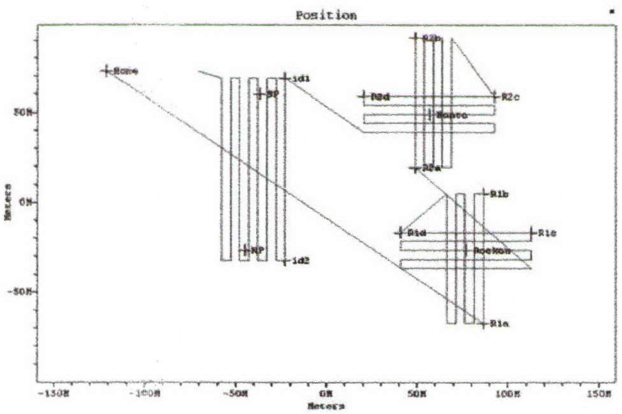


Fig. 7. Search Path. A + shaped reacquisition grid allows for multiple opportunities to image the target from different directions, while minimizing the amount of area that is needlessly searched.

V. RECOMMENDATIONS AND CONCLUSIONS

A. Sonar System Parameters

Based on a comparison of the results from testing the 1.2 MHz and the 2.4 MHz systems, it was decided that an intermediate frequency of 1.8 MHz with an aperture of 3.5" should be built and tested. This frequency and aperture combination produces the optimum beam width at the imaging range of 2.5 – 10 meters. Using a frequency of 1.8 MHz will also allow for 1.2 MHz filtration to be used to remove any remains of DVL interference.

To maximize the effectiveness of short range operation, the Range Delay feature available to users of the towed version of the Sea Scan PC software needs to be added to the UUV version of the software. Additionally, the TVG feature needs to be modified to allow for finer control in the ranges of interest to the R-I mission.

B. Vehicle Integration and Operational Considerations

The sonar transducers should be mounted on the vehicle with a depression angle of 20-30 degrees. This will facilitate operation at the desired altitude of 2-3 meters, while still obtaining sufficient ground coverage. Standard vehicle operational speeds of 2-3 knots give satisfactory imaging results for reacquisition and identification.

As the sonar systems are installed and operated on the REMUS and CETUS II vehicles, careful note should be taken of the integration issues and the steps necessary for their satisfactory resolution. Particular attention should be paid to the need for noise filtering and isolation.

C. Conclusions

Clearly, as these sonar systems are integrated onto the different vehicle platforms, there will be a continued need for test and evaluation under controlled conditions. In particular, concepts of operation and operational techniques need to be developed in order to get the most information possible from these sensors.

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Marine Automation and Robotic Engineering Laboratory, Perry Technologies

Space and Naval Warfare Systems Center UUV Lab

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